Induction motors

Types of fields (flux)

① pulsating field

* It has a fixed location in space
* Its magnitude varies according to the current producing it.

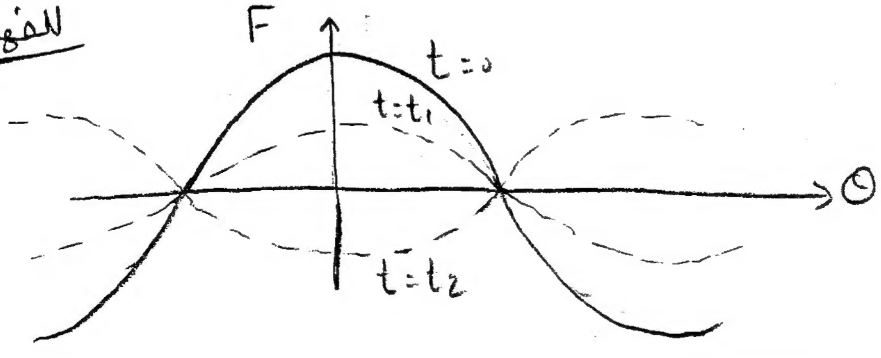
② Rotating field

* It has constant amplitude and rotates at constant speed around periphery of the machine.

"محيط"

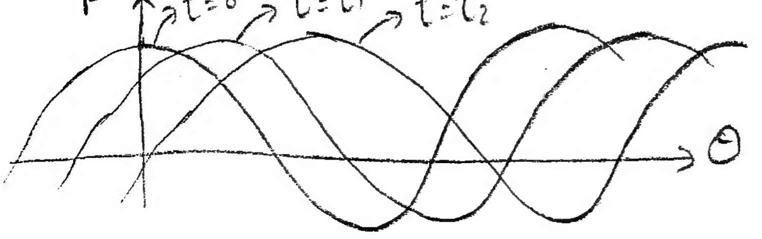
Ex: $MMF_1 = F_{max} \cos\omega t \cos\theta \Rightarrow$ pulsating

للفهم فقط



مع تغير الزمن
قيمة F تتغير لكن
مكان الـ peak ثابت

$MMF_2 = F_{max} \cos(\omega t - \theta) \Rightarrow$ Rotating



مع تغير الزمن مكان الـ
peak بيتغير

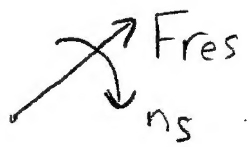
Rotating field theory

- If 3 phase balanced winding is supplied from 3 phase balanced source, then 3 phase balanced currents are produced
- Each current produce pulsating mmf (F_a, F_b, F_c)
- The resultant mmf F_{res}

$$F_{res} = F_a + F_b + F_c$$

- The resultant mmf is a rotating field which has constant magnitude & rotate with a constant speed (n_s)

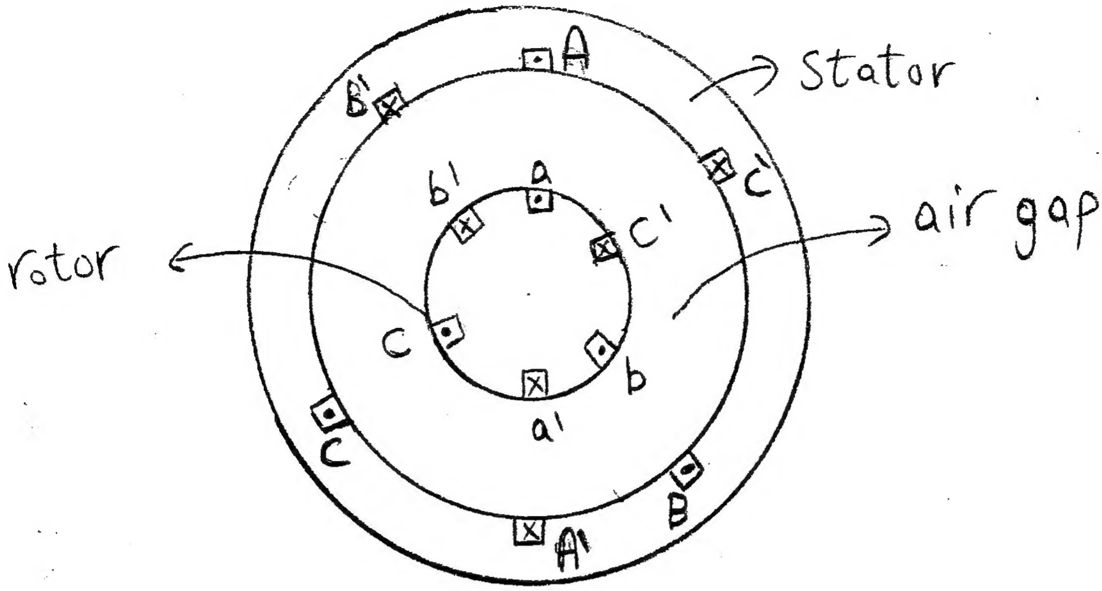
$$n_s = \frac{60f}{P}$$



Where n_s: Synchronous Speed (speed of rotating Field)

f : supply Frequency

Induction motor



⟹ Construction

It consists of

① Stator

* 3phase winding are placed on it
* They are shifted by 120° electrically.
* The 3 ph. windings are supplied by 3 phase balanced Ac Source
* The Stator is laminated, and have slots.

② Rotor

* 3phase winding are placed on it
* They are shifted by 120° electrically
* The Terminals of the 3-phase winding are short circuited.

* There are 2 types of rotors:

→ Types of rotors

① Squirrel cage

* This type of rotor is Shortcircuited and has no external terminals (Closed rotor), This type is Commonly used.
* Made of copper bars

(ii) slip ring

This type has three terminals through Carbon brushes & slip rings.

③ Air gap

* The spacing between stator & rotor
* It is used to:
  (i) allow rotor to rotate
  (ii) make the machine operate in linear part in order to avoid the operation in non-linear part (saturation) of B-H curve

Theory of operation

3 ph balanced windings supplied from 3ph balanced supply

$\Downarrow$

3ph balanced currents in stator I_a, I_b, I_c

$\Downarrow$

Rotating Field (Φ_s)

$\Downarrow$

3ph induced emf's (e_a, e_b, e_c) will be produced on rotor windings

$\Downarrow$

Rotor windings are short circuited, so 3ph balanced currents will flow in rotor windings (i_a, i_b, i_c)

$\Downarrow$

Rotating Field (Φ_r)

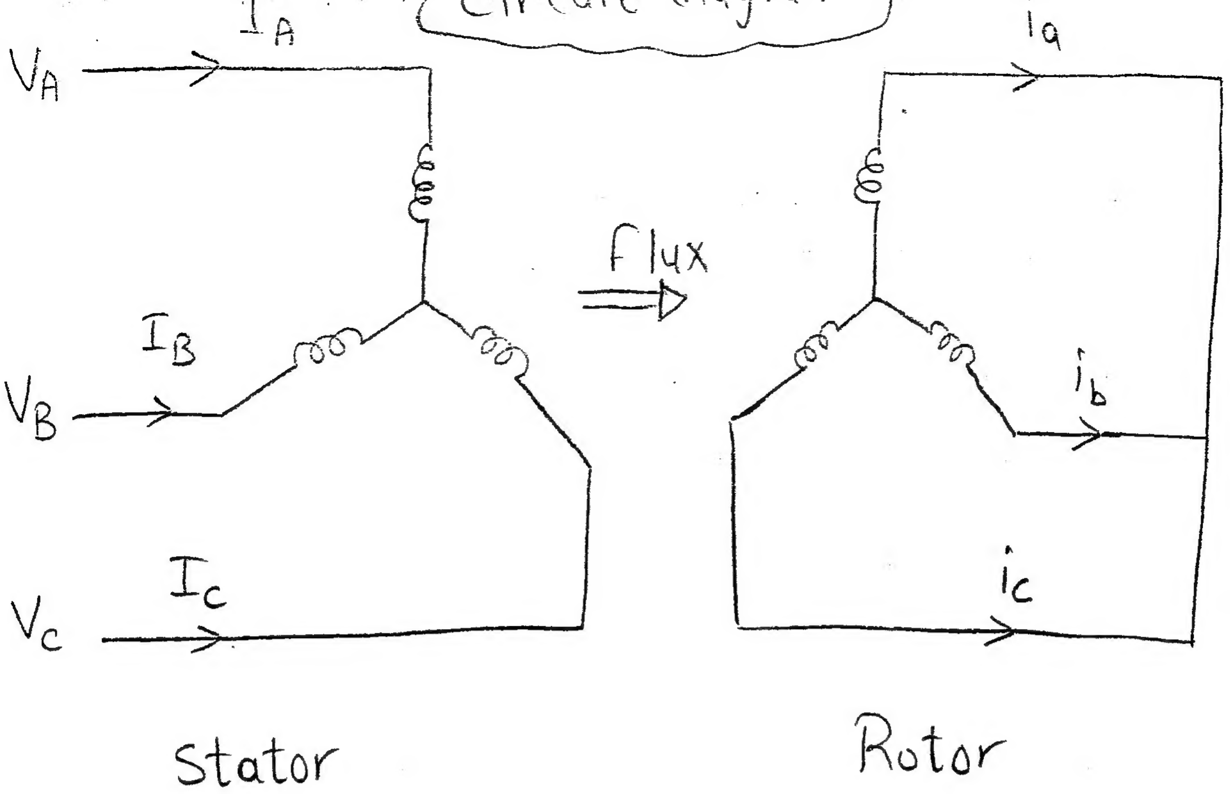
$\Downarrow$

The interaction between Φ_s & Φ_r produces torque

$\Downarrow$

The Motor rotates

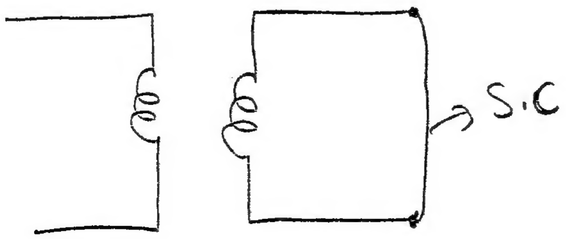
Circuit diagram



→ The theory of induction motor is similar to that of transformer, But the difference is that :

Induction motor has a <u>rotating</u> secondary winding, while the transformer is a static device.

→ <u>Circuit diagram of Induction motor</u> (1-phase)



Single phase representation (Single line diagram)

Speed & Frequency in Induction motor

* The stator field (Φ_s) & rotor field (Φ_r) rotate with the same speed (n_s)

$$n_s = \frac{60 F}{p}$$

n_s: synchronous speed

F: supply Frequency

p: Number of pole pairs

* The rotor speed is (n_r)
* The stator speed is (Zero) [Fixed body]

* The speed of stator field or Rotor field with respect to:
  - (i) stator body $\Rightarrow$ $n_s - 0 = n_s$
  - (ii) Rotor body $\Rightarrow$ $n_s - n_r$

* At starting (standstill), $n_r = 0$ (حالة خاصة)

$\therefore$ Speed of rotor field or stator field with respect to rotor body $= n_s$

Frequency of rotor current & Voltage

→ The Stator flux with speed (n_s) cuts the rotor windings with speed (n_r) so the produced emf and currents have a frequency (f_r)

$$n_s - n_r = \frac{60\, f_r}{P}$$

$$f_r = \frac{P}{60}\,(n_s - n_r)$$

$$f_r = \frac{P n_s}{60}\left(\frac{n_s - n_r}{n_s}\right)$$

$$f_r = f\left(\frac{n_s - n_r}{n_s}\right)$$

Let $S = \frac{n_s - n_r}{n_s}$ ⇒ Slip

$\therefore f_r = S f$ $\boxed{f_r \ll f}$

Where: f_r: frequency of emf & current induced in rotor

f: supply frequency

S: slip (It represents difference between stator field speed & rotor body speed)

Speed laws

هام

① $n_s = \frac{60 F}{P}$

- n_s: synchronous speed
- F: supply Frequency (usually 50 or 60 HZ)
- p: Number of pole pairs.
- 2p: Number of poles

② $S = \frac{n_s - n_r}{n_s}$

- S: slip
- n_r: rotor speed or motor speed

③ $F_r = SF$

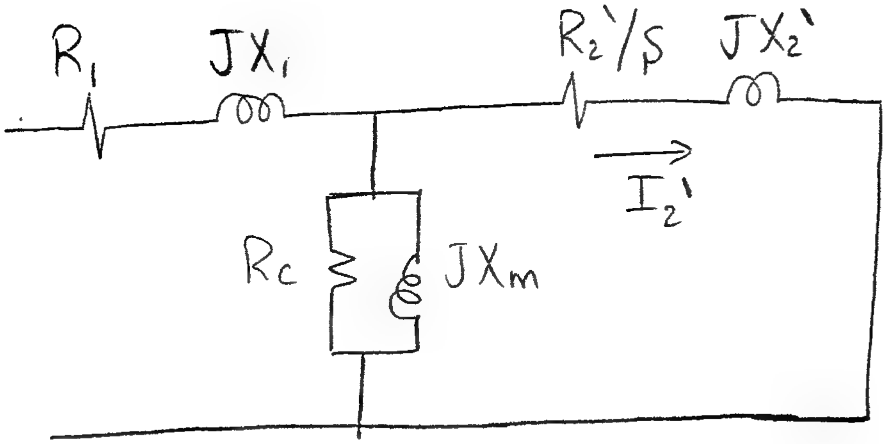
- F_r: Frequency of emf's induced in rotor winding
- F : supply frequency

④ * Speed of stator field & rotor field is $\underline{\underline{n_s}}$

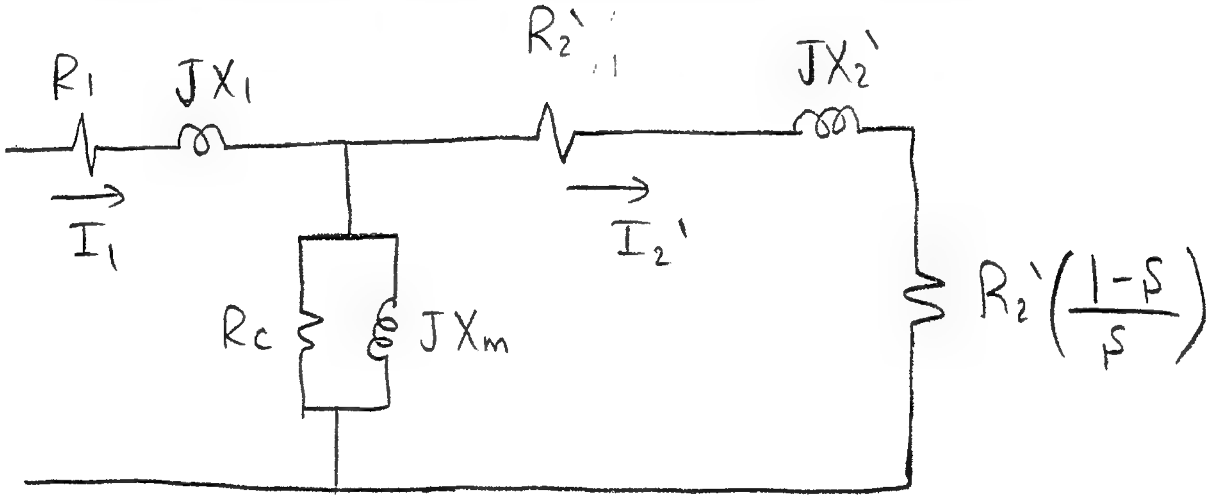
* speed of stator field or rotor field relative to rotor is $\underline{\underline{n_s - n_r}}$

Equivalent Circuit of induction motor

" للفهم فقط لم تذكر في المحاضرة "



Induction motor ≡ Transformer with S.C load



R_2' : Rotor resistance referred to stator

I_2' : Rotor current referred to stator

Types of power loss in induction motor

① Stator Copper loss ($P_{Cu\,stator}$)

Due to resistance of stator winding

② stator Core loss (P_{core})

Due to iron losses in stator core (eddy losses).

③ Rotor Copper loss ($P_{Cu\,rotor}$)

Due to resistance of rotor winding

④ Mechanical (rotational) losses

Due to friction that opposes the moving rotor.

Important note

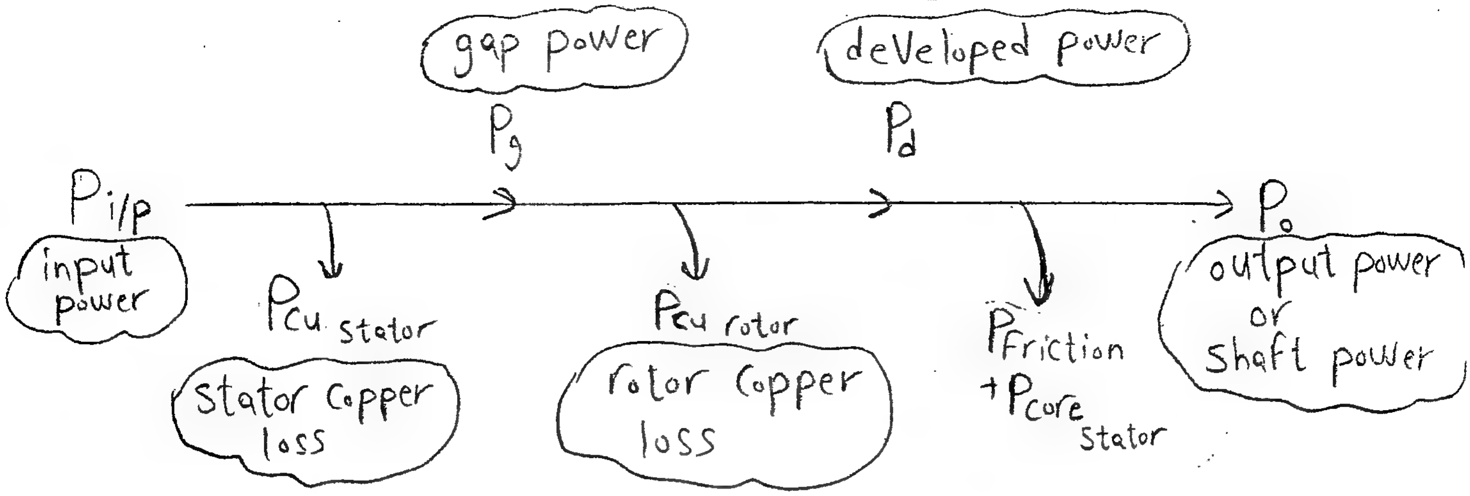
Rotor Core loss is neglected because

$P_{core\,rotor} = P_{e\,rotor} + P_{h\,rotor}$

* $P_{eddy\,rotor} \propto F_r^2$ * $P_{hystersis\,rotor} \propto F_r$

But $F_r = sF$ ($F_r \downarrow\downarrow$) $\Longrightarrow$ $P_{core\,rotor}$ is neglected.

power flow in induction motor



* $P_g = P_{i/p} - P_{cu_{stator}}$
* $P_o = P_d - (P_{Friction} + P_{core})$

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* $P_{i/p} = \sqrt{3}\ V_{L}\ I_{L}\ \cos\phi$
* $P_{cu_{stator}} = 3 I_s^2 R_s$
* $P_g = \dfrac{3 I_r'^2 R_r'}{s} = \dfrac{3 I_r^2 R_r}{s}$
* $P_{cu_{rotor}} = 3 I_r'^2 R_r' = 3 I_r^2 R_r^2$
* $P_d = 3 I_r'^2 R_r' \left(\dfrac{1-s}{s}\right) = 3 I_r^2 R_r \left(\dfrac{1-s}{s}\right)$
* $\boxed{P_d = (1-s) P_g}$

$\boxed{P_g = \dfrac{P_{cu\ rotor}}{s}}$

* $P_o = P_i - P_{cu_{stator}} - P_{cu_{rotor}} - P_{friction} - P_{core}$

* $\eta = \dfrac{P_o}{P_i}$

$$\eta = \frac{P_o}{P_o + P_{cu_{stator}} + P_{cu_{rototr}} + P_{friction} + P_{core}}$$

Note:

- P_g is called gap power or power input to the rotor

IF Torque is required

→ $T_d = \dfrac{P_d}{w_r} = \dfrac{P_g(1-S)}{w_s(1-S)} = \dfrac{P_g}{w_s}$

* T_d: electromagnetic developed Torque

* $w_s = \dfrac{2\pi n_s}{60}$

→ $T_{shaft} = \dfrac{P_{shaft}}{w_r} = \dfrac{P_o}{w_r}$

pb 7

* 3 phase Induction motor, 60HZ
* Shaft power = 80KW ($P_o = 80KW$)
* $P_{friction} = 920W$, $P_{core\ stator} = 4300W$, $P_{cu\ stator} = 2690W$
* $I_r' = 110A$, $R_r' = 0.15\Omega$, $S = 3.8\%$

Required $\Longrightarrow$ Find η

Solution

$\rightarrow$ $P_{cu_{rotor}} = 3(I_r')^2 R_r' = 3(110)^2(0.15\Omega)$

$P_{cu\ rotor} = 5.445KW$

$\rightarrow$ $P_{i/p} = P_o + P_{cu_{stator}} + P_{cu_{rotor}} + P_{friction} + P_{core}$

$= 80 + 2.69 + 5.445 + 0.92 + 4.3$

$= 93.35\ KW$

$\rightarrow$ $\eta = \frac{P_o}{P_i} = \frac{80}{93.35} = 85.7\%$

$\eta = 85.7\%$

pb. 8

- 3-ph I.M, 50HZ, 6 poles
- $P_i = 40KW$
- $n_r = 975$ rpm
- $P_{cu_{stator}} = 1KW$
- $P_{Friction} = 2KW$

Required: Find

(i) Slip (ii) P_{RCL} (iii) P_d (iv) η

Solution

$$n_s = \frac{60\,F}{P} = \frac{60 * 50}{3} = 1000 \text{ rpm}$$

(i) Slip

$$S = \frac{n_s - n_r}{n_s} = \frac{1000 - 975}{1000} = 0.025$$

$$S = 0.025$$

(ii) P_{RCL}

$* \; P_g = P_i - P_{Cu\,stator}$

$P_g = 40 - 1 = 39 \, KW$

$* \; P_{RCL} = S \, P_g = 0.025 * 39$

$P_{RCL} = 0.975 \, KW$

(iii) P_d

$P_d = (1-S) \, P_g = (1-0.025) * 39$

$P_d = 38.025 \, KW$ or $P_d = P_g - P_{RCL} = 38.025 KW$

(iv) η

$\Rightarrow P_o = P_d - P_{Friction} = 38.025 - 2 = 36.025 \, KW$

$\Rightarrow P_i = 40 KW$

$$\eta = \frac{P_o}{P_i} = 90.06\%$$

$\eta = 90.06\%$

pb. 9

- 3ph I.M , 50HZ, 6 poles
- power input to the rotor $(P_g) = 80KW$
- Rotor emf makes 100 alternations (cycles) per minute

Find

(i) Slip (ii) Motor speed (n_r) (iii) P_d

Solution

(i) $f_r = 100 \frac{\text{cycle}}{\text{min}} = 100 \frac{\text{cycle}}{60 \text{ sec}} = 1.667 \text{ HZ}$

but $f_r = SF$

$\therefore S = \frac{f_r}{F} = \frac{1.667}{50} = 0.033$

$\therefore S = 0.033$

(ii) $S = \frac{n_s - n_r}{n_s}$

but $n_s = \frac{120f}{P} = \frac{120(50)}{6} = 1000 \text{ rpm}$

$\therefore 0.033 = \frac{1000 - n_r}{1000} \Longrightarrow n_r = 967 \text{ rpm}$

(iii) $P_d = (1-S)\ P_g$

$\therefore P_d = (1-0.033) * 80$

$\therefore P_d = 77.36\ Kw$

pb.. (10)

- 3 ph I.M , 50HZ , 4 poles , $S = 0.05$

Find the speed of rotor mmF (Flux) relative to the rotor

Solution

$\Rightarrow$ Speed of rotor m.m.f $= n_s = \frac{60f}{P} = 1500$ rpm

$\Rightarrow$ Speed of rotor body $= n_r = (1-s)\, n_s = 1425$ rpm

$\therefore$ speed of rotor m.m.f relative to rotor body $= n_s - n_r = \boxed{75 \text{ rpm}}$

Ex: A 3phase, 2 poles, 60HZ induction motor operates at a speed of 3502 rpm with an input power of 15.3KW and terminal current of 22.6A. stator winding resistance $r_s = 0.2\,\Omega/\text{phase}$ calculate: ① air gap power

② Rotor Copper loss

Solution

Terminal current = Stator current

① $P_g = P_{i/p} - P_{cu_{stator}}$

* $P_{i/p} = 15.3\,KW$

* $P_{cu_{stator}} = 3I_s^2 R_s = 3(22.6)^2(0.2) = 0.306\,KW$

$\therefore P_g = 15.3 - 0.306 \Rightarrow P_g = 14.994\,KW$

② $P_{cu_{rotor}} = S P_g$

$$S = \frac{n_s - n_r}{n_s}$$

$$n_s = \frac{60f}{P} = \frac{60(60)}{1} = 3600$$

$$\therefore S = \frac{n_s - n_r}{n_s} = \frac{3600-3502}{3600} = 0.0272$$

$$\therefore P_{cu_{rotor}} = SP_g = (0.0272)(14.994)$$

$$P_{cu_{rotor}} = 407.8\,W$$

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Energy Conversion
Sheet (2)

Synchronous and Induction Machines
Dynamic Equations

1- Why is the stator core of Alternator laminated?

2- What are the losses in the 'induction motor' and briefly explain them?

3- In a 3-phase synchronous motor
(A) the speed of stator MMF is always more than that of rotor MMF.
(B) the speed of stator MMF is always less than that of rotor MMF.
(C) rotor and stator MMF are stationary with respect to each other.

4- Why almost all large size Synchronous machines are constructed with rotating field system type?

5- Why are Alternators rated in kVA and not in kW?

6- Write down the equation for frequency of emf induced in an Alternator.

7- The shaft output of a three-phase 60- Hz induction motor is 80 KW. The friction and windage losses are 920 W, the stator core loss is 4300 W and the stator copper loss is 2690 W. The rotor current and rotor resistance referred to stator are respectively 110 A and 0.15 Ω. If the slip is 3.8%, what is the percent efficiency?

8- The power input to a 500 V, 50 Hz, 6 pole 3 phase squirrel cage induction motor running at 975 rpm is 40 KW. The stator losses are 1 KW and the friction and windage losses are 2 KW. Calculate
(i) Slip (ii) Rotor copper loss
(iii) Mechanical power developed (iv) The efficiency.

9- The power input to the rotor of a 3-phase, 50 Hz, 6 Pole induction motor is 80 kW. The rotor emf makes 100 complete alternations per minute. Find
(i) the slip (ii) the motor speed and (iii) the mechanical power developed by the motor.

10- A balanced three-phase, 50 Hz voltage is applied to a 3 phase, 4 pole, induction motor. When the motor is delivering rated output, the slip is found to be 0.05. The speed of the rotor m.m.f. relative to the rotor structure is:
(A) 1500 r.p.m. **(B)** 1425 r.p.m.
(C) 25 r.p.m. **(D)** 75 r.p.m.

11- A three-phase, 500 MVA 20.8 kV four-pole star-connected synchronous machine has negligible stator resistance and a synchronous reactance of 0.8 Ohm per phase at rated terminal voltage. The machine is operated as a generator connected to a three-phase 20.8 kV infinite bus.
Note: 20.8 kV is the line voltage.
a Give the per-phase equivalent circuit of the synchronous machine.
b Calculate the phase voltage.
c Sketch the phasor diagram when the machine is delivering rated MVA at a power factor of 0.8 lagging.

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Synchronous and Induction Machines
Dynamic Equations

d Determine the excitation voltage and the power angle when the machine is delivering rated MVA at a power factor of 0.8 lagging.

12- For the system of Fig.1 the magnetic force is opposed by the inertial force, damping force and the spring force. Write down the force balance equation where:
c is the spring constant proportional to the displacement, *b* is the damping coefficient proportional to the velocity and *m* is the mass of the system.

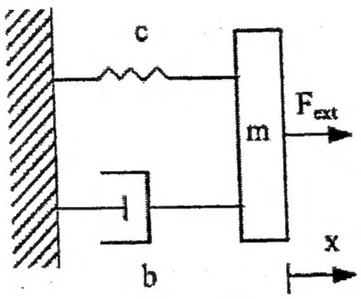

Fig.1: Mechanical system, Spring-Mass-Damper

13- Derive the electrical and mechanical equations of motion of the mechanical system shown in Fig.2.

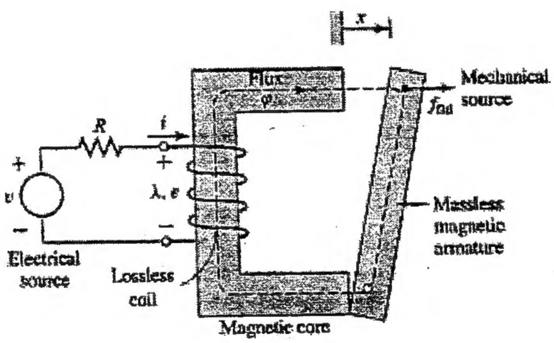

Fig.2: Electromechanical system